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14. ABSTRACT
The aim of this project was to explore 3D printing for RF/microwave circuits and devices. The research produced several 3D printed microwave filters, a 3D wifi radio circuit, and new materials for 3D printed electromagnetic devices. The research demonstrates that 3D printing is capable of manufacturing circuits and high-frequency microwave systems. Future work in this area should explore ways that the third dimension can be exploited to reduce size, weight, and power and how it can be used to incorporate physics that is not possible in three dimensions

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Final Technical Report

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Report Title

Final Report: HBCU/MI: 3D Formable RF Materials and Devices

ABSTRACT

The aim of this project was to explore 3D printing for RF/microwave circuits and devices. The research produced several 3D printed microwave filters, a 3D wifi radio circuit, and new materials for 3D printed electromagnetic devices. The research demonstrates that 3D printing is capable of manufacturing circuits and high-frequency microwave systems. Future work in this area should explore ways that the third dimension can be exploited to reduce size, weight, and power and how it can be used to incorporate physics that is not possible in three dimensions.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

J. Castro, J. Wang, and T. Weller, "High-k and Low-Loss Thermoplastic Composites for Fused Deposition Modeling and their Application to 3D-Printed Ku-Band antennas," 2016 International Microwave Symposium, June 2016.

N. Arnal, T. Ketterl, Y. Vega, J. Stratton, C. Perkowski, P. Deffenbaugh, K. Church, and T. Weller, "3D Multi-Layer Additive Manufacturing of a 2.45 GHz RF Front End," Microwave Symposium Digest (IMS), 2015 IEEE MTT-S International, pp. 17-22, May 2015

Number of Presentations: 2.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
09/27/2016	8.00	. Direct Digital Manufacturing of a 2.45 GHz Phased Array, 2016 URSI Conference. 16-SEP-16, Boulder, Colorado. : ,
09/27/2016	10.00	. High-k and low-loss polymer composites with co-fired Nd and Mg-Ca titanates for 3D RF and microwave printed devices: Fabrication and characterization, Wireless and Microwave Technology Conference (WAMICON). 16-SEP-16, Tampa, FL. : ,

TOTAL: **2**

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Schellenger Professorship in Electrical Engineering, 2015
Star on the Mountain Award, City of El Paso, 2015
2015 UT-Regents' Outstanding Teaching Award
2015 BUILDing SCHOLARS & College of Engineering Mentoring Award
Dean's Award for Teaching, 2015

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Edgar Bustamante	1.00	
Noel Martinez	1.00	
Ubaldo Robles	1.00	
FTE Equivalent:	**3.00**	
Total Number:	**3**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Raymond C. Rumpf	0.25	
FTE Equivalent:	**0.25**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Edgar Bustamante	1.00	
Noel Martinez	1.00	
FTE Equivalent:	**2.00**	
Total Number:	**2**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 2.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 2.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 2.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 2.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 2.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 2.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME
Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

1 a. University of South Florida

1 b. 3650 Spectrum Blvd
Suite 160
Tampa FL 336129446

Sub Contractor Numbers (c): 26-0203-72-61
Patent Clause Number (d-1):
Patent Date (d-2):
Work Description (e): The scope of the subcontractor was the following: USF will perform measurements of th
Sub Contract Award Date (f-1): 5/1/13 12:00AM
Sub Contract Est Completion Date(f-2): 4/30/16 12:00AM

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1 a. University of South Florida

1 b. Division of Sponsored Programs
140 Seventh Avenue S., KRC 3113
St. Petersburg FL 337015016

Sub Contractor Numbers (c): 26-0203-72-61
Patent Clause Number (d-1):
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Work Description (e): The scope of the subcontractor was the following: USF will perform measurements of th
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Sub Contract Est Completion Date(f-2): 4/30/16 12:00AM

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1 a. University of South Florida

1 b. 4202 East Fowler Ave.
Tampa FL 336209951

Sub Contractor Numbers (c): 26-0203-72-61
Patent Clause Number (d-1):
Patent Date (d-2):
Work Description (e): The scope of the subcontractor was the following: USF will perform measurements of th
Sub Contract Award Date (f-1): 5/1/13 12:00AM
Sub Contract Est Completion Date(f-2): 4/30/16 12:00AM

Inventions (DD882)

Scientific Progress

3D Printed Microwave Filters

Two version of microwave filters were design, manufactured by hybrid 3D printing, and tested. These were a stepped impedance filter and coupled-line filter. For comparison purposes conventional PCB filters were also manufactured and tested. The low-pass and the bandpass filters were designed and simulated using Ansys HFSS. The low pass filter was designed to have a cutoff frequency of 2.5 GHz. While the bandpass filter was designed on the same platform to work at 2.4 GHz with a fractional bandwidth of 10%.

Filter Models

Figure 1 shows our CAD model of the microwave filter with subminiature version A (SMA) connectors attached to each end. This model was generated directly in Ansys HFSS.

Technology Transfer

NA

Pioneering 21st Century
Electromagnetics and Photonics

FINAL PROGRESS REPORT

August 2016

HBCU/MI: 3D FORMABLE RF MATERIALS AND DEVICES

PREPARED BY:

UTEP Technical POC

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UTEP Administrative POC

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Agreement Number W911NF-13-1-01090

University of Texas at El Paso

Table of Contents

Statement of the Problem Studied

The aim of this project was to explore 3D printing for RF/microwave circuits and devices. The research produced several 3D printed microwave filters, a 3D wifi radio circuit, and new materials for 3D printed electromagnetic devices. The research demonstrates that 3D printing is capable of manufacturing circuits and high-frequency microwave systems. Future work in this area should explore ways that the third dimension can be exploited to reduce size, weight, and power and how it can be used to incorporate physics that is not possible in three dimensions.

Submissions and Publications

Table Summary

Category	Number
Papers	
Peer-reviewed	7
Non-peer reviewed	1
Presentations	
Meetings	0
Non-peer reviewed conferences	2
Peer-reviewed conferences	0
Manuscripts	2
Books	1
Honors and Awards	0
Patents	
Disclosed	0
Awarded	0

Titles

Manuscripts and Presentations

- Ubaldo Robles, Noel Martinez, Edgar Bustamante, Raymond C. Rumpf, "Microwave filters manufactured by hybrid 3D printing," in progress for submission to IEEE MTT, Fall 2015.
- Ubaldo Robles, Noel Martinez, Edgar Bustamante, Raymond C. Rumpf, "3D Printed Wifi Module," in progress for submission to IEEE TAPS, Fall 2015.
- J. Castro, E. Rojas, A. Perez, T. Weller and J. Wang, "Enhancement of Microwave Dielectric Properties of Polymer-Ceramic Composites with MgCaTiO2 and TiO2 Micro-fillers through a High-Temperature Sintering Process," Journal of American Ceramic Society, to be submitted in August (2016).
- D. Hawatmeh, S. LeBlanc, P. Deffenbaugh, and T. Weller, "Embedded 6 GHz 3D-Printed Half-Wave Dipole Antenna," in IEEE Antennas and Wireless Propagation Letters, vol. PP, No. 99, pp. 1-1.
- Maria Cordoba and Thomas Weller, "Non-Destructive Characterization of Polymer-Coated Samples by Near-Field Microwave Microscopy," submitted to Review of Scientific Instruments, September 2015.

- Thomas P. Ketterl, Yaniel Vega, Nicholas C. Arnal, John W. I. Stratton, Eduardo A. Rojas-Nastrucci, María F. Córdoba-Erazo, Mohamed M. Abdin, Casey W. Perkowski, Paul I. Deffenbaugh, Kenneth H. Church, Member, and Thomas M. Weller, "3D Multi-Layer Additive Manufacturing of a 2.45 GHz RF Front End," in Microwave Theory and Techniques, IEEE Transactions on, Vol. 63, no. 12, pp. 4382-4394, Dec. 2015.
- Thomas Ketterl, Casey Perkowski, Paul Deffenbaugh, John Stratton, Joshua Stephenson, Kenneth Church, and Thomas Weller, "Direct Digital Manufacturing of a 2.45 GHz Phased Array," 2016 URSI Conference – invited paper, Boulder, Colorado, January 2016.
- Juan Castro, Eduardo Rojas, Thomas Weller and Jing Wang, "Engineered Nanocomposites for Additive Manufacturing of Microwave Electronics," 2015 IMAPS, October 2015.
- Castro, Juan; Rojas, Eduardo; Weller, Thomas; Wang, Jing, "High-k and low-loss polymer composites with co-fired Nd and Mg-Ca titanates for 3D RF and microwave printed devices: Fabrication and characterization," Wireless and Microwave Technology Conference (WAMICON), 2015 IEEE 16th Annual , vol., no., pp.1,5, 13-15 April 2015.
- N. Arnal, T. Ketterl, Y. Vega, J. Stratton, C. Perkowski, P. Deffenbaugh, K. Church and T. Weller, "3D Multi-Layer Additive Manufacturing of a 2.45 GHz RF Front End," Microwave Symposium Digest (IMS), 2015 IEEE MTT-S International , vol., no., pp., 17-22 May 2015.
- J. Castro, E. Rojas, T. Weller and J. Wang, "High-k and Low-Loss Thermoplastic Composites for Fused Deposition Modeling and Their Application to 3D-Printed Ku-Band Antennas," submitted to IEEE Trans. MTT, June 2016.
- Kenneth H. Church, Nathan Crane, Paul I. Deffenbaugh, Thomas P. Ketterl, Clayton Neff, Patrick Nesbitt, Justin Nussbaum, Casey Perkowski, Harvey Tsang, Jing Wang, and Thomas M. Weller, "Multi-Material and Multi-Layer Direct Digital Manufacturing of 3D Structural Microwave Electronics," submitted to IEEE Proceedings, June 2016.
- J. Castro, E. Rojas, T. Weller and J. Wang, "High-Permittivity and Low-Loss Electromagnetic Comp Ba0.55Sr0.45TiO3 or MgCaTiO2 Micro-Fillers for Additive Manufacturing and Their Application to 3D-Printed K-Band Antennas," the Journal of Microelectronics and Electronic Packaging, accepted for publication May 8, 2016.
- J. Castro, J. Wang and T. Weller, "High-k and Low-Loss Thermoplastic Composites for Fused Deposition Modeling and their Application to 3D-Printed Ku-Band Antennas," 2016 International Microwave Symposium, June 2016.

Honors and Awards for Raymond C. Rumpf

- Schellenger Professorship in Electrical Engineering, 2015
- Star on the Mountain Award, City of El Paso, 2015.
- 2015 UT-Regents' Outstanding Teaching Award.
- 2015 BUILDing SCHOLARS & College of Engineering Mentoring Award.
- Dean's Award for Teaching, 2015.

Supported Personnel Metrics

Support Summary

Name	% Supported	%FTE
Graduate Students	**300%**	**150%**
Edgar Bustamante	100%	50%
Noel Martinez	100%	50%
Ubaldo Robles	100%	50%
Post Doctorates	**0%**	**0%**
Faculty	**25%**	**25%**
Raymond C. Rumpf	25%	25%
Undergraduate Students	**200%**	**100%**
Edgar Bustamante	100%	50%
Noel Martinez	100%	50%
Other Research Staff	**0%**	**0%**

Graduating Undergraduate Metrics

Category	Number
B.S. Degrees	
Graduated this period	2
Graduated this period in STEM	2
Graduated and will continue through Ph.D.	2
Graduated with GPA 3.5 to 4.0	2
Funded by DoD Center of Excellence	0
Intend to work for DoD	2
Receive Scholarships or Fellowships	2
M.S. Degrees	0
Ph.D. Degrees	0

Technology Transfer

No technology transfer activities have yet occurred.

Summary of the Most Important Results

3D Printed Microwave Filters

Two version of microwave filters were design, manufactured by hybrid 3D printing, and tested. These were a stepped impedance filter and coupled-line filter. For comparison purposes conventional PCB filters were also manufactured and tested. The low-pass and the bandpass filters were designed and simulated using Ansys HFSS. The low pass filter was designed to have a cutoff frequency of 2.5 GHz. While the bandpass filter was designed on the same platform to work at 2.4 GHz with a fractional bandwidth of 10%.

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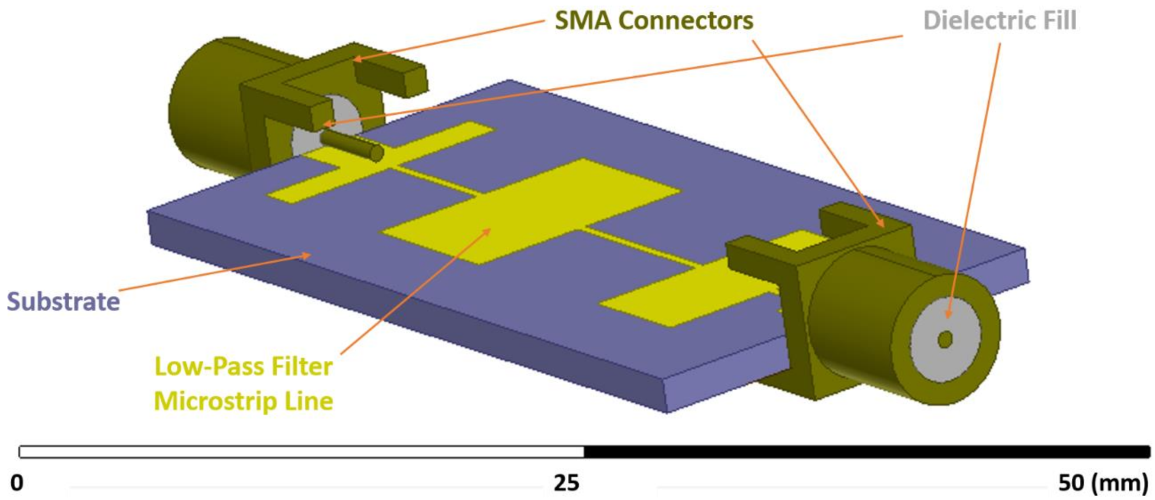


Figure 1. Top view of CAD model of stepped-impedance microwave filter.

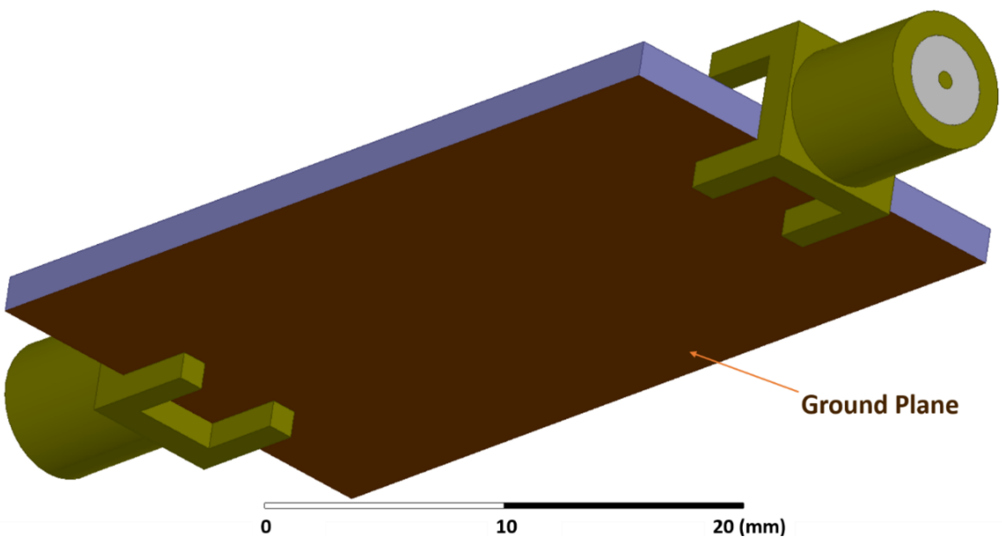


Figure 2. Bottom view of CAD model of stepped-impedance microwave filter.

The dimensions of this devices are provided in Figure 3. Figure 4 shows the dimensions of the ground plane and the substrate; both of these have the same area. It is important to note that the height of the microstrip line and ground plane were defined as an infinitely thin sheet to improve our HFSS simulation speed. Typical values for the height of the ground plane and microstrip on manufactured microwave filters would be around 0.10 mm. The height of the substrate was set to 1.6 mm.

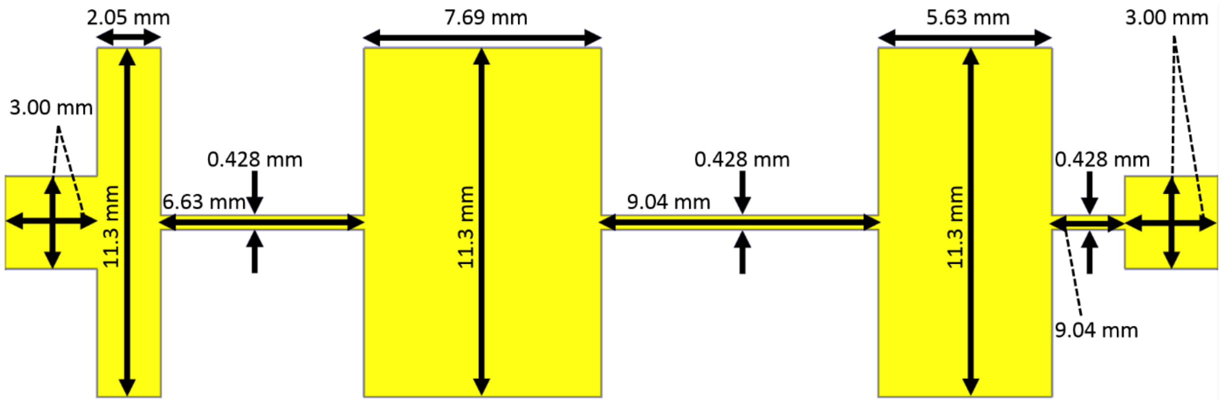


Figure 3. Low pass filter microstrip dimensions.

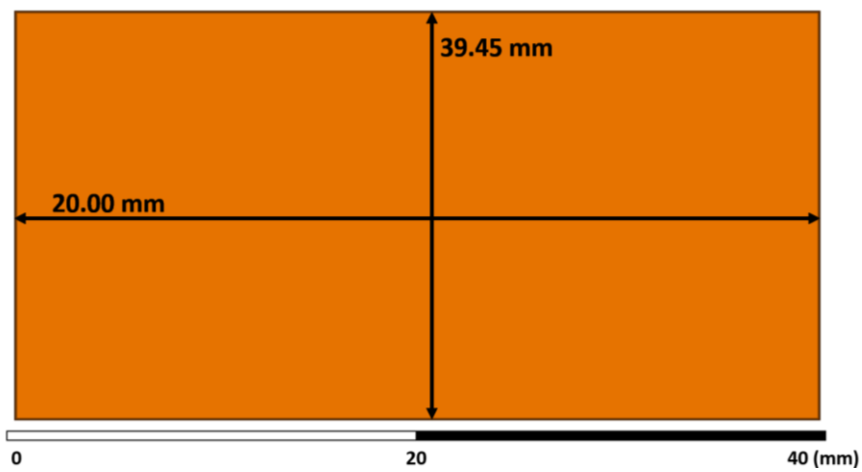


Figure 4. Filter ground plane and substrate dimensions.

Figure 5 shows the design we calculated for the bandpass filter.

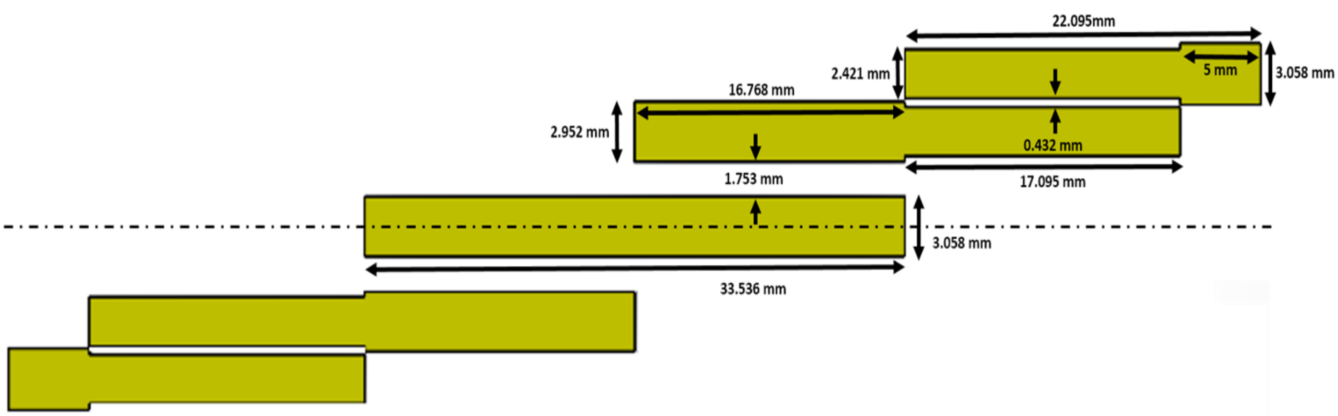


Figure 5. Bandpass filter microstrip dimensions

The conventional microwave filters were manufactured on FR4. Material properties of copper were assigned to the microstrip line and ground plane in the Ansys HFSS simulation. The substrate was assigned the FR4-Epoxy material properties available from the materials library in Ansys HFSS. The SMA connectors were set to have brass material properties while the dielectric fill had Teflon material properties. Finally, the filters were simulated on ANSYS HFSS. Figure 6 shows simulation parameters for the filters that go as follow: the substrate chosen is FR4 with a permittivity of 4.4, the wave ports are used as feeds, and the whole structure is enclosed inside a radiation box.

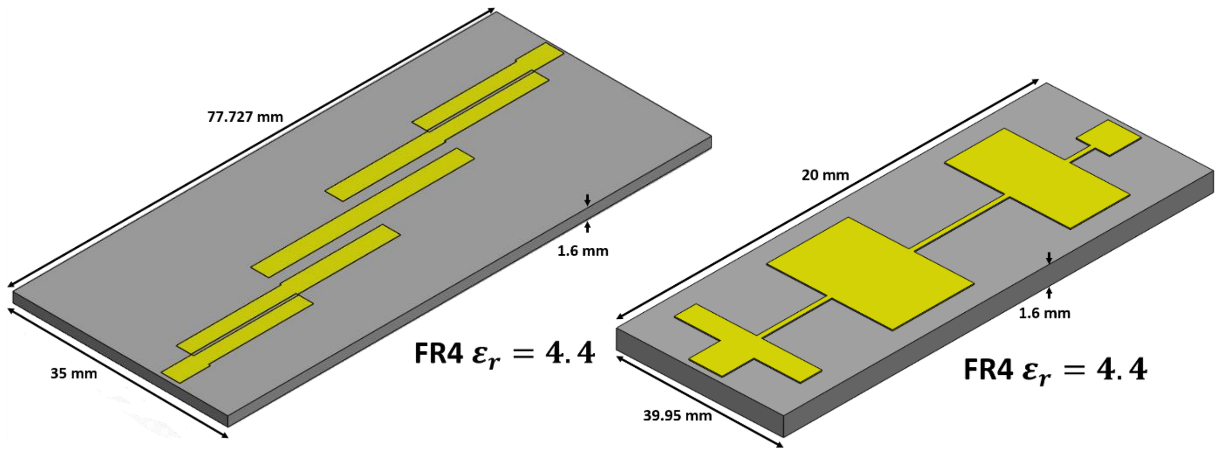


Figure 6. Filters use in Ansys HFSS simulations

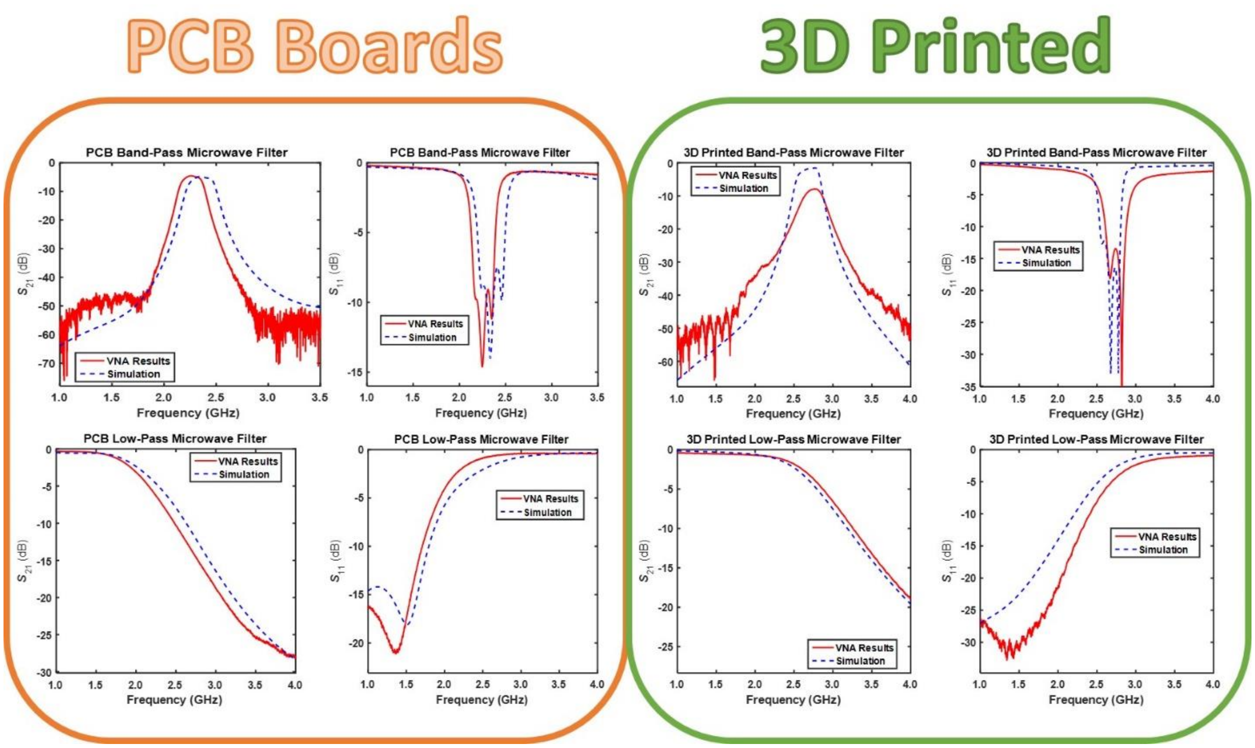


Figure 7. Comparison of simulated and measured results for both PCB and 3D printed RF filters.

Figure Filter Results

Figure 7 shows the simulated and measured scattering (i.e. S_{21}, S_{21}) for both filters. The cutoff centered at 2.5 GHz is obvious. This data shows that the 3D printed and conventional filters perform very similarly. The primary differences were the conductivity of the metals and the dielectric constant of the substrate material.

Microwave Filter Manufacturing

Our first microwave filters were manufactured using conventional PCB technology and 3D printing. The devices were designed in EAGLE and sent for manufacturing outside of UTEP. Figure 8(left) shows the top view of the PCB before the SMA connectors were soldered onto it. Figure 8(right) shows the bottom view of the same device. A second version of this microwave filter was manufactured by hybrid 3D printing. Both were characterized in the lab.

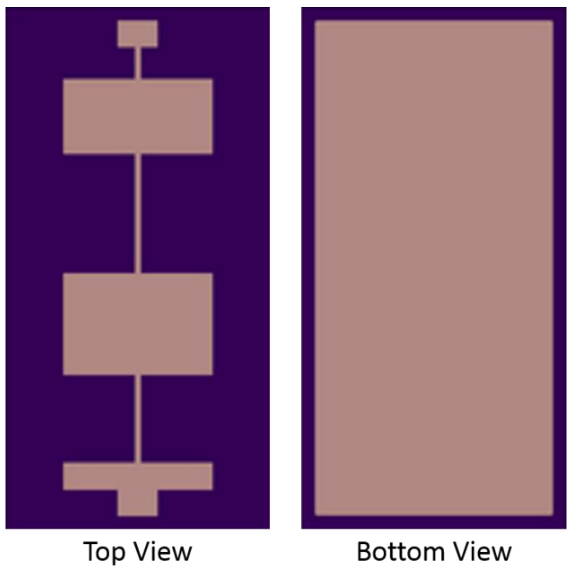


Figure 8. Standard PCB microwave filter design.

3D Printed Microwave Filter

In this research we required capabilities of a hybrid system that can handle two materials and heat curing. We used an nScrypt Table Top 3D printer that has capabilities to print two different materials between filament plastics and resins with different viscosities. In addition to the two materials we had a need to cure with heat due to the silver ink curing requirements.

Two material printing was necessary in this effort since we needed to fabricate the structure of the substrate where the filter geometry needed to rest on. The materials were dispensed by two processes: dispensing the silver conductive inks we used nScrypt's second generation SmartPump^{TM} 100 system. The fuse deposition process for the ABS plastic material that form the substrate was built by using nScrypt's nFD pump. The nScrypt printer has great capabilities, however, there are adjustments needed in order to create pristine parts. Typically, one needs to adjust the dispensing gaps between material pumps, the pen tips used to create the metallic geometries, and the speeds that the materials are being dispensed at. These adjustments are necessary to avoid printing mistakes, poor quality surfaces, and more importantly reliable devices. The high frequency filtering devices we manufactured required high reliability and very

precise features down to the microns. Our nScrypt 3D printing system was able to perform for us down to the 10 μm accuracy as shown in Figure 9.

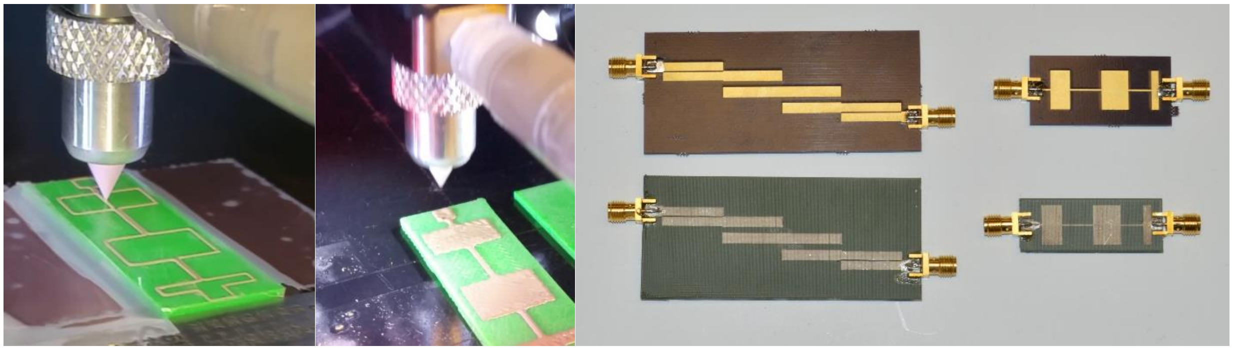


Figure 9. 3D Printing manufacturing process compared to conventional PCB filters

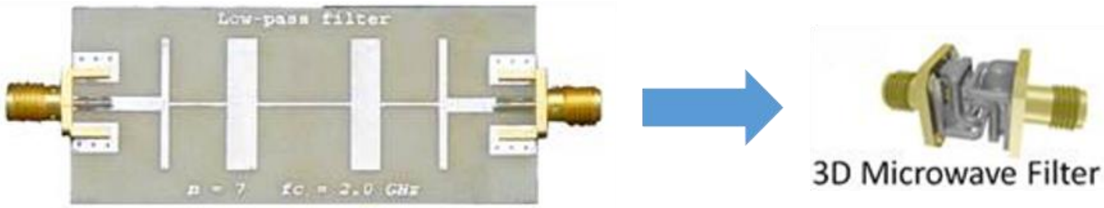


Figure 10. Illustration of 3D microwave filter concepts made possible by 3D printing

3D Printed Radio

Planar Circuit Design

The design of the radio comes from the ESP8266 system-on-a-chip (SOC) shown in Figure 11. This SOC serves as a Wi-Fi adapter and operates at a frequency of 2.4 GHz. We chose to replicate this module due to the simplicity of the circuit and the low number of circuit traces it contains. Figure 12 shows the two-dimensional circuit design we designed in SolidWorks.

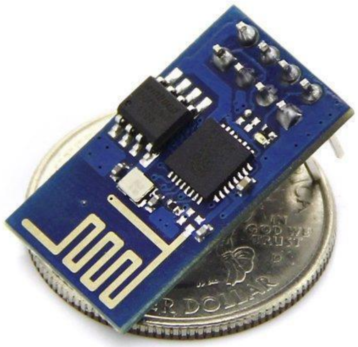


Figure 11. ESP8266 Wi-Fi Module

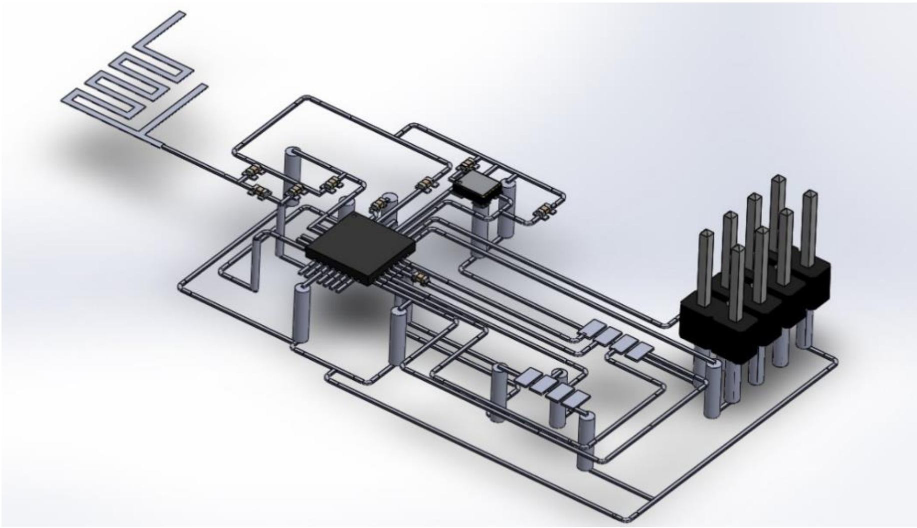
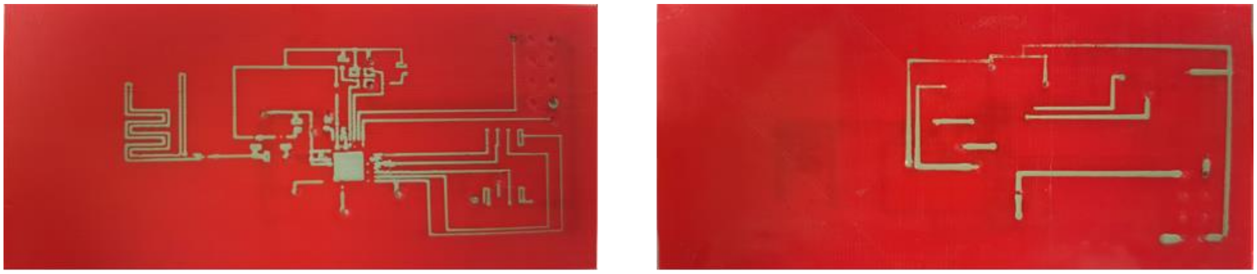


Figure 12. SolidWorks CAD Model of ESP8266 circuit

RF Radio Manufacturing

To 3D print this RF device, two printing methods were used. FDM was used to print the substrate of the circuit out of acrylonitrile butadiene styrene (ABS) plastic, while micro-dispensing was used to print the circuit traces out of silver conductive ink. At the time this circuit was manufactured, we did not have a machine that combined both of these 3D printing techniques so they were performed in two separate steps. First we 3D printed the circuit substrate from ABS. Second, we printed the circuit traces on top of and the bottom of the substrate. Figure 13 shows photographs one of the finished 3D printed circuits.



(a) (b)

Figure 13. 3D printed radio of ESP8266 circuit. (a) Top layer of the board. (b) Bottom layer of the board.

Populating Components

We are currently in the process of populating the circuit boards that were printed as this has proved particularly challenging for us. To place the surface mount technology (SMT) components from the ESP8266 onto the 3D printed circuits, we designed a solder paste stencil. This stencil, shown in Figure 14, provides us with the precision necessary to place conductive silver epoxy on the contact pads without creating any shorts between adjacent circuit traces.

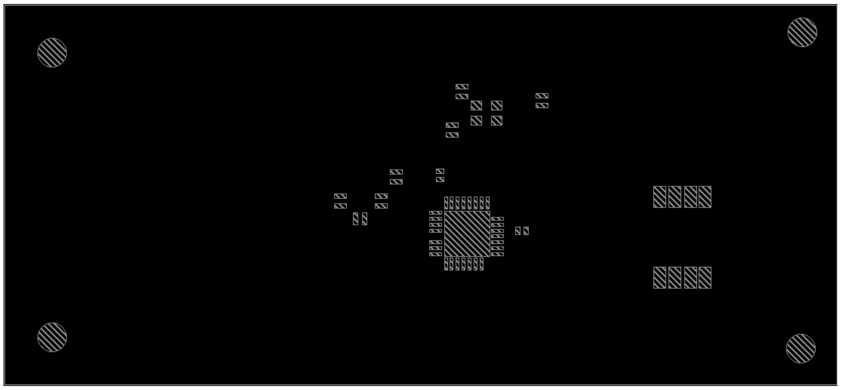


Figure 14. Solder paste stencil design.

Verification Plan

To verify that our Wi-Fi circuits were printed successfully, we created a computer program that uses an Arduino UNO board to toggle a LED through a web page interface. We intend to connect the Arduino to the internet using our 3D printed Wi-Fi radio. Once connected, the Arduino will wait for a signal from the web page to toggle the LED on or off and send back the status of the LED.

References

[1] Espressif Systems, "Espressif Smart Connectivity Platform: ESP8266," ESP8266 datasheet, Oct. 2013.

Materials Development

Advanced Materials for Digital Manufacturing

Summary – A systematic approach has been adopted to develop flexible high-k and low-loss polymer-ceramic composites, by dispersing high-permittivity nano/microparticles into the Sylgard 184 PDMS silicone elastomer with volume loading concentration up to 49%. The microwave composites were characterized up to 20 GHz using cavity resonators. The composite material is currently being used for 3D printing of microwave electronics.

3D additive manufacturing (3D AM) has received tremendous attention from research communities in several scientific disciplines and industry due to the great potential as versatile and accurate rapid prototyping technology [9]. For instance, 3D AM of antennas and other RF and microwave devices when compared to conventional processes, provides additional design freedom by taking advantage of the z-plane that can be leveraged for microwave circuit and antenna miniaturization [1]. In recent years several RF devices have been successfully demonstrated as reported previously [1]-[4], which makes the 3D AM technology a promising enabler for the next generation of RF and microwave devices. However, there are important challenges to be overcome to fully adopt the technology for RF/microwave applications. In particular, the lack of high-permittivity (high-*k*) and low-loss 3D printable materials at microwave and millimeter wave frequencies seriously hinders the ability for AM technology to be adopted in RF and microwave electronics, which it will be addressed in this research.

This work has focused on development of high-k polymer-ceramic composites using Sylgard 184 PDMS as the host polymer. The preparation of nanocomposites starts with mixing

of the two components of the PDMS in a 10:1 ratio by using a planetary centrifugal mixer (ARE-310), followed by a deaeration (also known as "degassing") step for removing any trapped air bubbles. The second step is to determine the volume ratio between the co-fired ceramic fillers and the host polymer based on the powder density. The planetary centrifugal mixer is used to mix the ceramic powders and the PDMS host matrix at the desired volume concentration while ensuring homogenous dispersion. The resultant polymer-ceramic composites are then poured into a custom-designed hot compression mold followed by a careful degassing step at 22 in-Hg using an isotemp vacuum oven (model 281A) to remove the air bubbles. A degassing time more than 2 hours is needed for high filler loading beyond 20% in volume including purging steps every 10 minutes. The sample is then compression molded and cured at 100°C for 1 hour. The ceramic powders were fully analyzed with XRD and SEM for morphology and crystallinity before and after a high temperature co-firing process was applied. This high temperature co-firing process is a critical step for enhancing the dielectric and loss properties of the ceramic powders.

The dielectric properties of composite substrates at microwave frequencies were evaluated through the cavity resonator method by using Agilent 8720ES network analyzer (50 MHz to 20GHz) and two different commercial thin dielectric sheet testers from Damaskos, Inc. One test fixture is for the low frequency band of 0.4 to 4.4 GHz and the other covers the high frequency band of 6.2 to 19.4 GHz. The cavity resonator testers work under the cavity perturbation technique. It is well known that the complex permittivity can be found from the resonant frequency shift and variation of Q factor of a rectangular cavity inserted with a small sample as explained in [5]-[7].

In our experiments, it was observed that the primary loss of the polymer-ceramic composites arises from the PDMS host polymer matrix as shown in Figure 15. From the high-frequency performance, the best balance between high permittivity and low loss was achieved with the PDMS-$MgCaTiO_2$ based composite sample, while both composite materials have shown fairly frequency-independent high dielectric permittivity and slightly lower loss tangent as compared to prior works [8]-[10]. The measured microwave dielectric and loss properties of both composite elastomer substrates are superior to that of the widely-used FR-4 printed circuit boards in terms of relative permittivity and dielectric losses, while almost approaching the characteristics of some rigid fiberglass-based high-end microwave laminates (e.g., TMM10, TMM10i and TMM13i from Rogers Corp.)

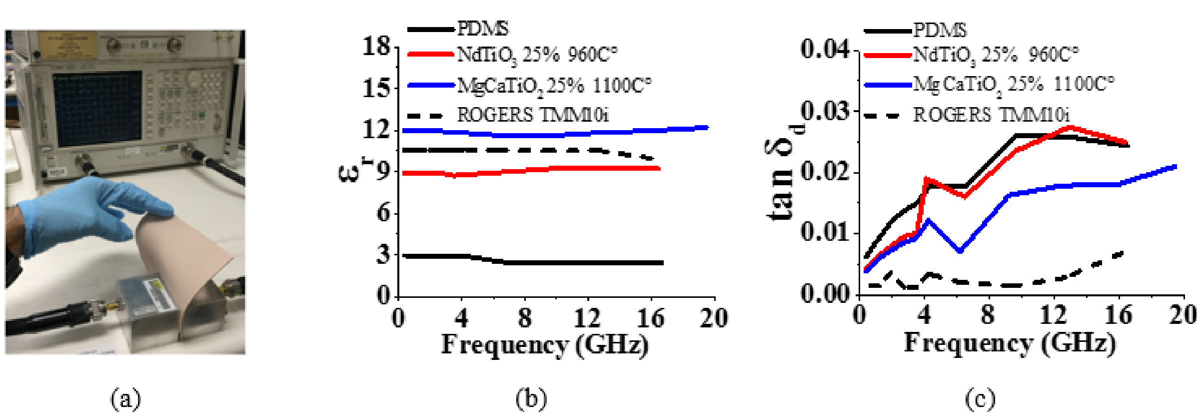


Figure 15. Measured EM properties including: (a) a photo of the measurement setup; (b) measured permittivities; and (c) loss tangents for samples of PDMS, 25% PDMS-$NdTiO_3$ with $NdTiO_3$ powders co-

fired at 960°C, PDMS-$MgCaTiO_2$ with 25% of MgCaTiO2 powders co-fired at 1100°C and Rogers TMM10i Laminate[2].

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Materials Characterization using Non-Contact Near-Field Microwave Microscopy (NFMM)

Summary – Traditional techniques for determining the high frequency, complex permittivity of materials include the use of cavity resonators, dielectric probes or printed transmission line structures (e.g. resonators). These methods are generally not compatible with testing materials such as un-cured pastes, which are common to the digital printing domain. Microwave microscopy itself is not a new technique, but to the best of our knowledge this is the first demonstration of accurate printed electronics characterization.

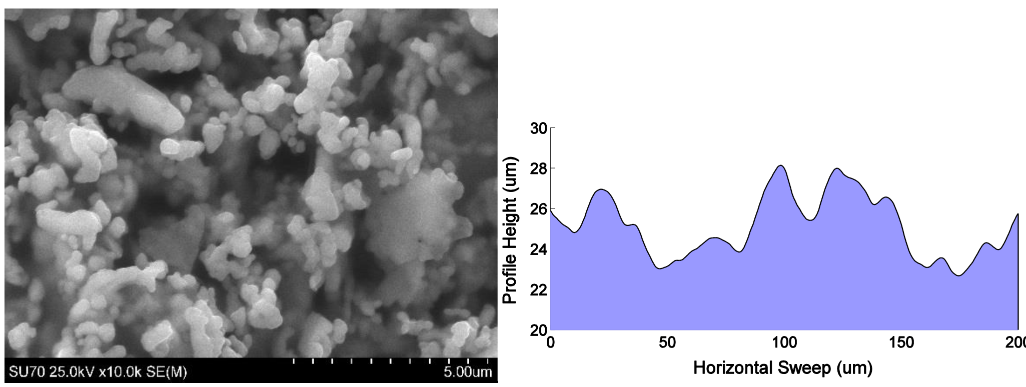
Conductive inks are key materials that are being used in Direct Digital Manufacturing (DDM) for the fabrication of circuits and devices. The implementation of Ag thick film conductive ink has been reported for more than 30 years [1]. One of the advantages that this material offers is that it can be easily printed over a 3D surface while requiring a relatively low curing temperature (160° C for CB028) [2]. Previous works [3-5] characterized the curing process, electrical and surface properties of the material, using the conductivity calculated using DC measurements such as four-point probe, serpentine pattern, or Van der Paw technique. The use of this material in the realization of antennas [6], and more recently in the fabrication of microwave circuits [7]-[8] show the need of a characterization method at RF frequencies which provides localized material properties, rather than a averaged value. Typical techniques used to measure electrical conductivity of printed traces provide an averaged value of the electrical resistivity and do not show localized variations of the resistivity over the sample's surface, which can affect the performance of the printed structures, particularly for high frequency applications.

The fact that DDM technology generates highly rough surfaces and the sintering process of the ink results in an inhomogeneous particle distribution in the micron scale, escalates the

importance of a measurement that provides conductivity with high spatial resolution, while at the same time resolving the surface relief. NFMM is a non-contact, non-destructive technique used to measure the electromagnetic properties of materials such as dielectric constant, electrical conductivity and permeability on length scales shorter than the wavelength at the operation frequency [9].

In this work, we measure the localized electrical conductivity of several conductive printed traces using a non-contact NFMM operating at 5.73 GHz. The conductive traces are made using CB028 silver ink, and a micro-dispense pump system.

A SEM image over an area of 12 μm x12 μm of the surface of the ink after the curing process is shown in Figure 16(a). The SEM image was acquired using a Hitachi SU-70. The particle size of the ink after the curing process ranged between 0.5 μm to 4μm, with an average size of 2 μm, in agreement with [3]. A 200 μm profile across the sample was also measured using a Veeco Dektak 150 profilometer and is shown in Figure 16(b).



(a) **(b)**

Figure 16. Properties of the cured silver ink. (a) SEM image of the surface of a 25.2 um (average) thick sample. (b) Segment of profile of the same sample.

A photograph of the NFMM used in this work is shown in Figure 17. It consists of an 8753 vector network analyzer (VNA) which is used as microwave source and detection system, a dielectric resonator (DR) -based microwave probe and a XYZ positioning system. The DR-based microwave probe operates at 5.73 GHz and consists of a dielectric resonator mounted on a RO4350B substrate and magnetically coupled to two 50 Ω microstrip lines. A commercially available gold-coated tungsten tip with radius of 25 μm is attached to a microstrip line 3λ/4 long. The resonant probe is enclosed in an aluminum cavity in order to prevent radiation and degradation of the resonator quality factor. The tungsten tip protrudes beyond one of the walls of the cavity through a hole with diameter of 5 mm.

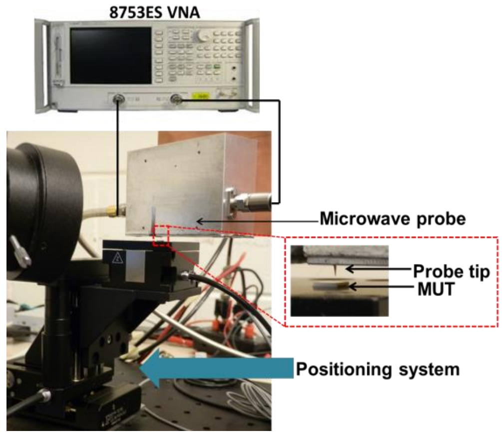


Figure 17. Photograph of the 5.73 GHz scanning near-field microwave microscope.

The imaging capability of the NFMM was studied by scanning a sample over an area of 100 μm x 100 μm in steps of 2 μm. At each point of the scan, Q and topography were simultaneously acquired. Then Q data were converted to electrical conductivity using a calibration curve. Figure 18(a) and (b) show the electrical conductivity and topography images obtained, respectively. The conductivity distribution in Figure 18(a) indicates that the conductivity is not constant but varies between 0.6e6 S/m - 2e6S/m. Higher conductivity regions are observed over lower areas in the topography.

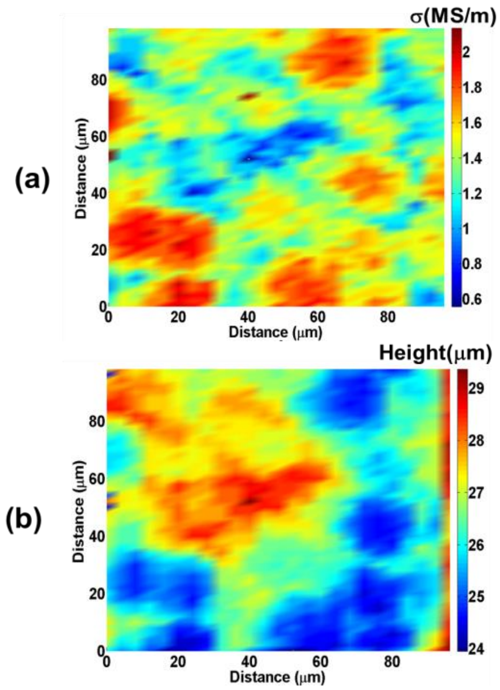


Figure 18. Conductivity and topography images over an area of 100 μm x100 μm obtained using the NFMM.

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